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Laboratory studies of the charge transferred when ice micro crystals rebound off an ice surface have continued. It is now widely accepted that thunderstorms are electrified by such interactions. A large cloud chamber allows us to grow ice crystals up to 800µm and these collide with an ice target representing a falling graupel pellet. Our previous work showed that the presence of supercooled water in the cloud is of paramount importance and the precise effect this has on the charge reversal temperature (above which graupel charges positively and vice versa) is being investigated so that the results may be included in numerical models of thunderstorm electrical development. Individual interactions have been studied and the results

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confirm the earlier work using multiple collisions. Collision and collection efficiencies of graupel for ice crystals have been measured for the first time and the data may also be included in models of both hailstone growth and of thunderstorm electrification. The results of the charge transfer experiments showed that with larger crystals, the net charge transferred is less than had been predicted from earlier studies with smaller crystals. We suggest that this effect is due to local corona discharge when an ice crystal separates from the graupel pellet. The emission of light during this event was predicted and has now been observed. This result has a profound significance to charge transfer mechanisms as it is linked to the trapping of charge on the local areas of contact. Further work into these effects and into high speed collision events continues.

This report has been reviewed by the EOARD Information Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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LARGE ICE CRYSTAL CHARGE TRANSFER STUDIES

GRANT No. AFOSR-87-0379

28 OCTOBER 1988

INTERIM SCIENTIFIC REPORT
1 SEPTEMBER 1987 - 31 AUGUST 1988

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Introduction

The USAF provided us in 1985 with a large cold-room in which thunderstorm conditions can be simulated. A 3m tall cloud growth chamber within the cold-room permits an extended fall-time of ice crystals so that they can grow to sizes of several hundred microns. Previously, crystals up to about 120μm were the maximum size that could be grown in the laboratory. The experiments performed so far have been concerned with the electrical charging of graupel pellets due to collisions with ice crystals, which we believe to be the most important charging mechanism inside thunderstorms. We have also investigated high speed interactions to simulate aircraft charging due to cloud particle collisions. A report to the USAF was submitted in September 1987 which gives details of our work up to that time. Our work for the present contract, from August 1987 is summarised in this interim report.

The Work to Date

The cloud chamber in the cold-room is shown in Figure 1. In order to make large ice crystals, the top chamber is filled with water droplets from an atomizer and these supercool to the environmental temperature. Ice crystals are nucleated by introducing a fine metal wire, cooled to liquid nitrogen temperature, into the top chamber. The crystals grow while the droplets evaporate due to their different equilibrium vapor pressures. As the crystals grow, they fall, and in order to extend their growth time air is drawn out of the top of the chamber at a controlled rate so the crystals are just levitated. After this initial growth period the trap-door is opened, the updraft turned off, and the crystals fall into the supersaturated environment of the lower chamber, where they continue to grow to sizes up to about

800μm diameter. At the bottom of the chamber a rotating frame carries metal rods as targets which quickly become covered in rime-ice and simulate a graupel pellet falling through a thunderstorm in an environment of supercooled water droplets and ice crystals. Crystals bouncing off the target separate electric charge and the net current passes through slip-rings via amplifiers to recorders. Two other arms of the target support a hot-wire device for measuring the cloud liquid water content, and a glass target on which is mounted a platinum resistance thermometer for measuring the ice surface temperature. The cloud droplet and crystal concentration and size distributions are determined by drawing the cloud past glass slides covered in plastic replicating solution which can subsequently be examined under a microscope.

Experiments have been performed to measure the collision and collection efficiencies of the target for ice crystals. It is not possible to model the aerodynamics of irregular objects such as ice crystals when they are carried in an airstream around a target and no data has been available to date. By coating the targets with a thin layer of plastic solution and with a knowledge of the absolute values of crystal concentration in the cloud, the collision efficiency may be found by counting the number of crystals deposited on the target. With a dry-replicator technique, the collection efficiency is determined from the collision efficiency and the number of crystals sticking to a dry plastic-coated target. Figure 2 shows the plate-crystal collision efficiency results for a 5mm diameter target at various speeds. Using these data and similar data for column crystals, together with the crystal collection results, Figures 3 and 4 were determined for plate and column crystals respectively. The

collection efficiency is seen to increase rapidly with increase in crystal size up to about 100μm, then to fall steadily for larger crystal sizes. These results imply that falling hailstones do collect ice crystals in their path, a result that has not been incorporated in models of hailstone growth which hitherto have been assumed to grow by riming only. These results will also be essential in developing models of electric field growth in thunderstorms which rely on bouncing interactions between ice crystals and graupel pellets to provide the charge separation. Many of our experiments have been concerned with charge transfer to a riming target under a range of conditions with a view to understanding the charge transfer process. In particular, the new cold-room facility has permitted us to extend the studies to large ice crystals. Previously, a relationship between charge transfer and crystal size had been found of the form $q \propto d^4$. This relationship, determined for crystals in the size range up to 125μm was then extrapolated in theoretical models of electric field development to millimetre-sized crystals as found in thunderstorms. In this way it was shown that the crystal interactions with a riming target are able to separate sufficient charge to account for thunderstorm electrification. However, the extrapolation using $q \propto d^4$ was completely unjustified. With corrected values of the separation probability of ice crystals, the small crystal data give a $d^{3.4}$ relationship. The new results with large crystals now show that the charge transfer follows the forms shown in Figures 5 and 6 for positive and negative charging respectively. The $d^{3.4}$ relationship is only valid up to about 150um and then it falls to $d^{0.3}$ for 800um crystals. These new data now need to be incorporated in models together with the collection efficiency results mentioned above. Figures 5 and 6

indicate that the charge transfer is being limited in some way, particularly at larger crystal sizes. It seemed likely that the limiting mechanism may be corona discharge a the point of separation of the interacting particles. Calculations showed that this may indeed be possible. The ultimate test was to look for the emission of light from rebounding crystals. Using a sensitive photo-cell close to the interaction zone, light output was detected. This important result has been investigated further, as it will affect all charge transfer mechanisms involving interacting cloud particles.

The limited effect is unlikely to be due to corona discharge over the whole surface of the crystal, because the critical charge for corona is of the order of pico-Coulombs for the size of crystals involved, whereas femto-Coulombs are being transferred. Also, we performed separate experiments at very high interaction speeds, above those relevant to thunderstorms, and found the charge to be orders of magnitude higher than in the experiments at lower velocities, indicating that at normal collision speeds we have not reached some inherent limit to the amount of charge that ice crystals can hold.

An experiment was performed in which a photo-diode viewed the zone of interaction between ice crystals and an ice target which simulated a soft hailstone. The crystals were grown from a cloud of supercooled water droplets, then the crystals plus droplets were drawn past the ice target. The apparatus was kept in the dark and when the charge transfer was detected, light emission was also noted. The output was two to three orders of magnitude larger than the dark noise. A check was made, by shielding the photo-diode optically but not electrically, that the output was not due to direct electrical pick-up from the

corona. The output obtained when crystals of 100μm diameter bounced off the target at 8 m/s corresponded to the emission of 6×10^5 photons per separating crystal. (The concentration of crystals and their collision and separation probabilities were determined separately.) Large resultant charge transfers, significant to the electrification of thunderstorms, were noted when the cloud contained both super-cooled water droplets and ice crystals. Weak charge transfer were noted when the droplets were absent and crystals alone bounced off the target. The light emission followed the same trend being higher in the presence of liquid water and lower for crystals alone. Light was emitted for both positive and negative charging of the ice target, the sign of the charge being influenced by the temperature. The charge transfer increased with crystal impact velocity, as did the light output. It was also noted that light was emitted for all sizes of crystals but that the emission increased with crystal size as shown by Figure 7, which presents values of the average number of photons detected for an individual charge transfer event per femto-Coulomb of net charge transfer plotted against crystal size. An analysis of the net charge transfer, q, and the associated number of photons emitted revealed a $q^{2.5}$ relationship with a correlation coefficient of 0.9.

We suggest that during the glancing contact of an ice crystal with a soft hailstone, so much charge is transferred that when the particles separate, a high electric field is set up which leads to a corona dischage and associated light emission. Despite the low surface conductivity of ice, there is apparently sufficient contact time for the initial charge transfer to occur but insufficient time for the charges to re-distribute over the surface before the particles separate. Thus every interaction

leads to an initial charge transfer and a subsequent reverse charge flow when the particles separate, so the net transfer appears to be limited.

A calculation can be made to confirm that the initial charge transfer is adequate to produce a sufficiently high field to cause a corona discharge when the particles separate. The initial charge transfer is, of course, unknown, but it must be larger than the net transfer measured. This transfer can be used to make an estimate of the contact area over which charge is transferred between the particles. Assuming the crystal and the soft hailstone surface can be considered locally as a pair of flat plates, the Gauss law may be applied to determine the contact area ($q/\varepsilon_o E$), where q is the net charge transferred and E is the critical electric field across the gap. (During separation, the field remains constant giving time for the corona discharge to occur.) The limited electric field at the surface of an ice crystal is of order 10^6V/m . A 100um crystal separates a net charge of 10 fC, for which the contact area is about 10% of the crystal area. For 500μm, the ratio is 11% while for 50μm it decreases to about 2%. Thus, using conservative values of the electric charge transferred, the contact areas determined are considerably smaller than the crystal surface areas involved. The initial charge transfers require larger contact areas but the point is made that adequate charge is present to lead to corona discharge. The fact that the interacting particles finish up with substantial residual charge rather than losing it all in the discharge process, indicates that there is time for some of the charge originally transferred during the period of contact to leak away from the local area or become trapped in the crystal lattice. Obviously, larger initial charge transfers, with larger

crystals, lead to more charge being available for the return process. The discharge process limits the net charge transfer by returning some of the charge initially separated before it has time to leak away.

The significance of these corona limited charge transfer results is that they must be taken into account in any theories of ice/ice particle charging in thunderstorms, as well as in determinations of the net effect throughout a thunderstorm of multiple charge transfer events. For large crystals, the charges actually transferred are less than would be expected from extrapolations of charge transfer data obtained with small ice crystals. The experimental values of charge transfer obtained as a function of crystal size, together with appropriate values of collision and separation probabilities, now need to be included in numerical models of thunderstorm electrical development, while the implications of the locally trapped charge on the interacting surfaces have to be studied from the theoretical viewpoint of charge transfer in ice.

The rotating charge transfer apparatus measures a continuous current to the target due to multiple ice crystal interactions. The question arose as to whether individual interactions were all of the same sign under given conditions and whether some crystals separated more charge than others. The apparatus was modified to permit crystals to be drawn into a wind-tunnel, levitated while they grew and reduced in number by the winnowing effect of the air stream. Eventually, a small number of 200μm diameter crystals were drawn out of the wind-tunnel past a stationary rimed target and the individual charge transfer events were noted. Figure 8 shows the number of charge transfer events for particular charge transfer observed. They are all positive and these

values are the same order as those in Figure 5 for multiple interactions of 200μm crystals. This gives added credibility to the multiple interaction technique which is far easier to handle than the single crystal method.

A further question about the multiple interaction technique is being investigated. The target in those experiments is effectively grounded through the current measuring circuit and so charge does not build up on the target. In thunderstorms, hail pellets may build-up sufficient charge to limit or affect subsequent charge transfers. By isolating one of the targets and measuring its accumulated charge intermittently, its charging rate can be compared with the other target which is used in the usual way. The results so far suggest that there is an effect of charge on the target; if the target is charged negatively then its rate of positive charging is higher than if it had not been charged. This implies that a negative hail-pellet falling from the negative charge center in a thunderstorm will charge rapidly in the positive charging region of the storm and so the lower positive center can be formed more easily than expected. (At cold temperatures, -20°C, hail pellets charge negatively; at warmer temperatures, -5 to -10°C, pellets charge positively; for details, see the 1987 report.)

Future Studies

The intent is to increase further our understanding of thunderstorm charging processes so that reliable predictions of thunderstorm behaviour may be made from a knowledge of the atmospheric conditions. It appears that electrification is associated with the ice phase in thunderstorms and the details of the charge transfer dependence on the temperature and particles sizes is

crucial to our understanding of the electrical development within storms.

The experiments to date have all used a moving ice-covered rod to simulate a falling graupel pellet. This was done because there is insufficient transfer of charge to give a detectable charge when an ice pellet is dropped through a laboratory cloud of ice crystals and supercooled water droplets. Now, however, with the new 3m chamber, we calculate that it should be possible to detect the charge on an ice pellet after it has interacted with the crystals in a 3m fall distance. A series of induction rings through which the ice sphere will fall have been arranged on a vertical support through the chamber and these have been linked to a microcomputer which will sample the voltages induced as the ice sphere falls through the cloud. This will be the most realistic simulation to date of charging in thunderstorms.

There has been renewed interest lately in the inductive theory of thunderstorm electrification in which the field itself leads to charge transfers between ice crystals and hail-pellets which then intensify the field. The mechanism has been questioned for reasons of inadequate surface conductivity and collision efficiency problems. By setting-up a vertical electric field in the chamber, realistic conditions for inductive electrification will exist; the final charge resulting on the hail pellet having fallen through the cloud will be measured by collecting it in a Faraday can connected to an electrometer. This method will overcome all the criticisms of previous studies which have had one or more questions raised about the techniques used.

The crystals grown in the chamber are large enough to collect supercooled droplets and to rime-up as they fall. It is

possible that interactions between these rimed crystals and smaller un-rimed crystals may lead to charge transfer. This has not been investigated to date but is possible in the new chamber and may be important in thunderstorm electrification.

The emission of light is associated with corona produced when crystals, having transferred charge with the target, bounce-off and then lose charge by local corona emission. The objectives of further study will be to investigate the effect for various crystal types, sizes and temperatures. Of importance will be the nature of the target, (rime-covered or smooth) and the presence or absence of supercooled water droplets. Our studies have shown that large charge transfer occurs when there are droplets present in the cloud; it is believed the droplets are responsible for vapour deposition on the crystals and the target leading to favourable charge transfer conditions. Thus, rougher surfaces lead to larger charge transfers. It would seem, however, that a rougher target surface covered with rime ice would initiate corona more easily than a smooth, unrimed target and this should lead to reduced net charge transfer.

It is intended to make a preliminary study of the scavenging of small aerosol particles by the large crystals in the chamber. There is a deficiency in our understanding of the process at present in that theory and previous experimental results do not agree. The problem with the experiments has probably been lack of realistic cloud situations; as with the charge transfer, the surface state of the ice crystals is likely to be important.

The charge transfer results have shown that liquid water in the form of supercooled water droplets is essential for charge transfer to be substantial enough to account for observed thunderstorm electrification. However, the presence of liquid water

also controls the transition temperature between positive and negative charge transfer. The charging is positive above about -15°C with a liquid water content of about 1gm m^{-3} and the transition temperature moves colder at higher liquid water contents. The present results are at present being augmented to obtain data at a range of liquid water content values over the temperature range of interest. These results can then be used in computer models of thunderstorm electrical development which take into account the details of the cloud microstructure to give a more accurate prediction of electrification from a given set of initial conditions.

Previous work has shown that when 100μm ice spheres bounce off metal targets, the sign of the charge transferred depends on the work function of the metal. Now it is possible to repeat this work with large ice crystals at impact speeds up to 100m/s, thus simulating aircraft impacts with ice crystals in the anvil of thunderstorms and in high altitude cirrus. Various target materials will be used in the presence and absence of liquid water to cover the range of conditions likely to be encountered.

A start has been made on incorporating the data from our charge transfer experiments into theoretical models of electric field development in thunderstorms. We have done some of this work ourselves with a simplified model. Other workers have developed sophisticated models of thunderstorm development into which our data on charge transfer values can now be input; we intend to work with them on this aspect of the work.

Conclusion

The continued support of this work has permitted us to make good use of the large ice crystal cold-room facility in UMIST.

Charge transfer values under realistic conditions are being obtained at present which will lead to a better understanding of thunderstorm electrification. High speed impacts will simulate aircraft and rocket charge transfer interactions with ice crystals. The data will be incorporated in models of thunderstorm development.

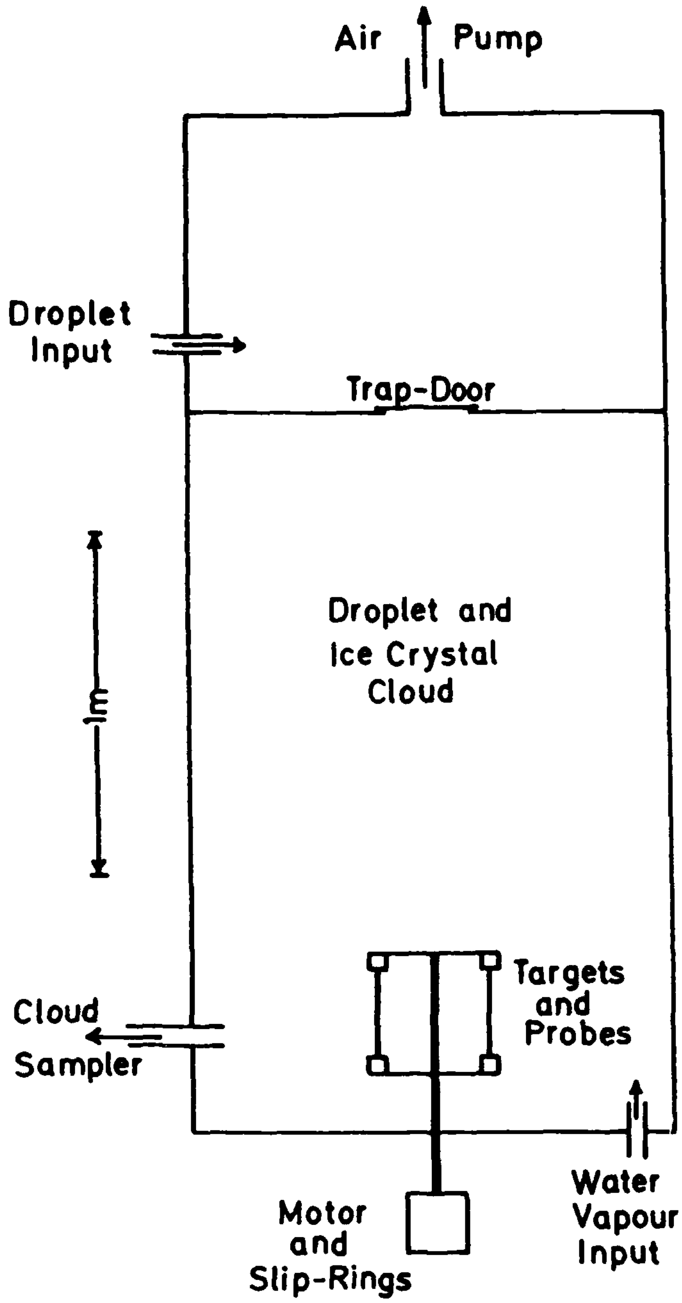


Figure 1

The cloud growth chamber inside the cold-room.

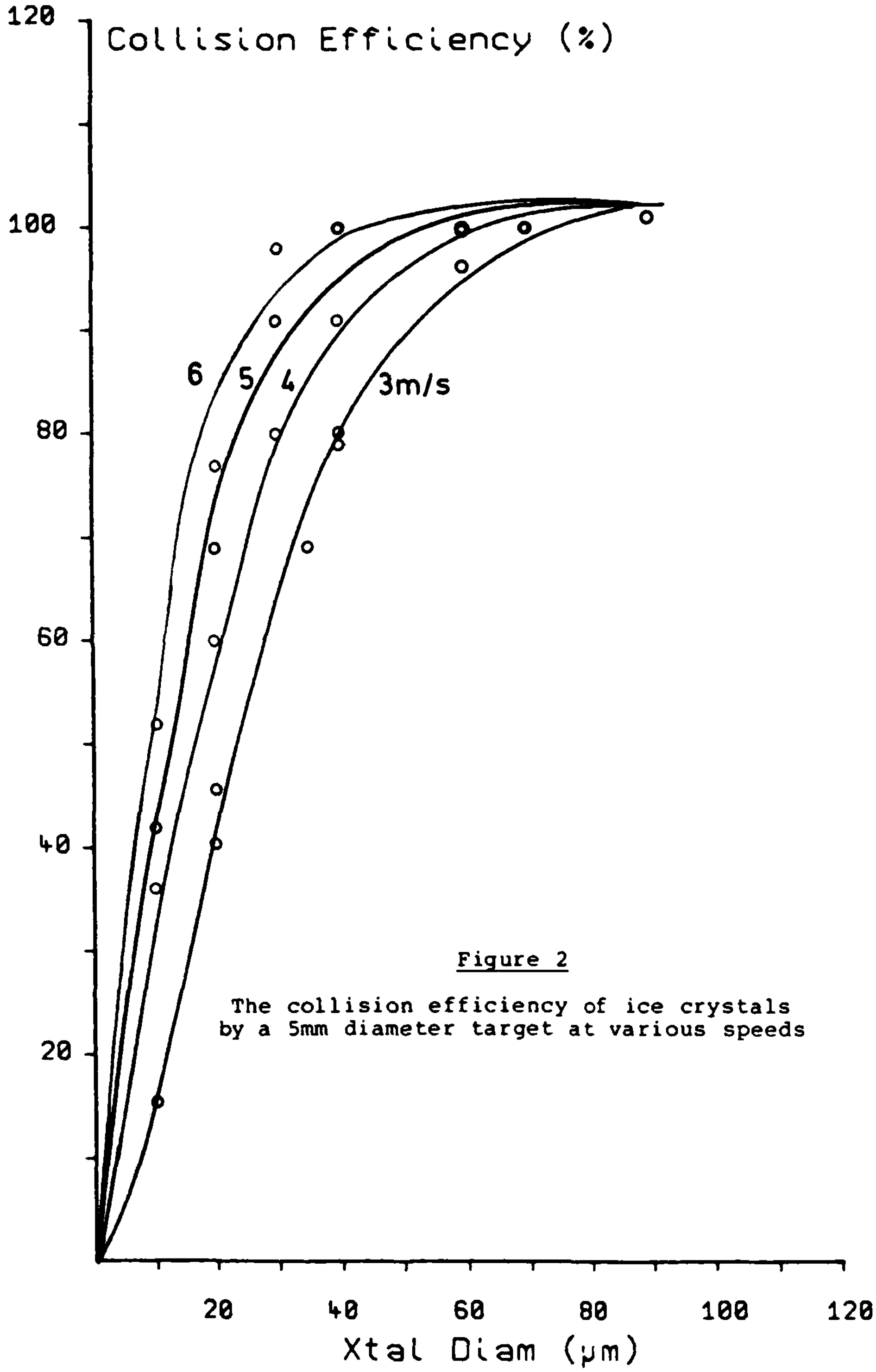


Figure 2

The collision efficiency of ice crystals by a 5mm diameter target at various speeds

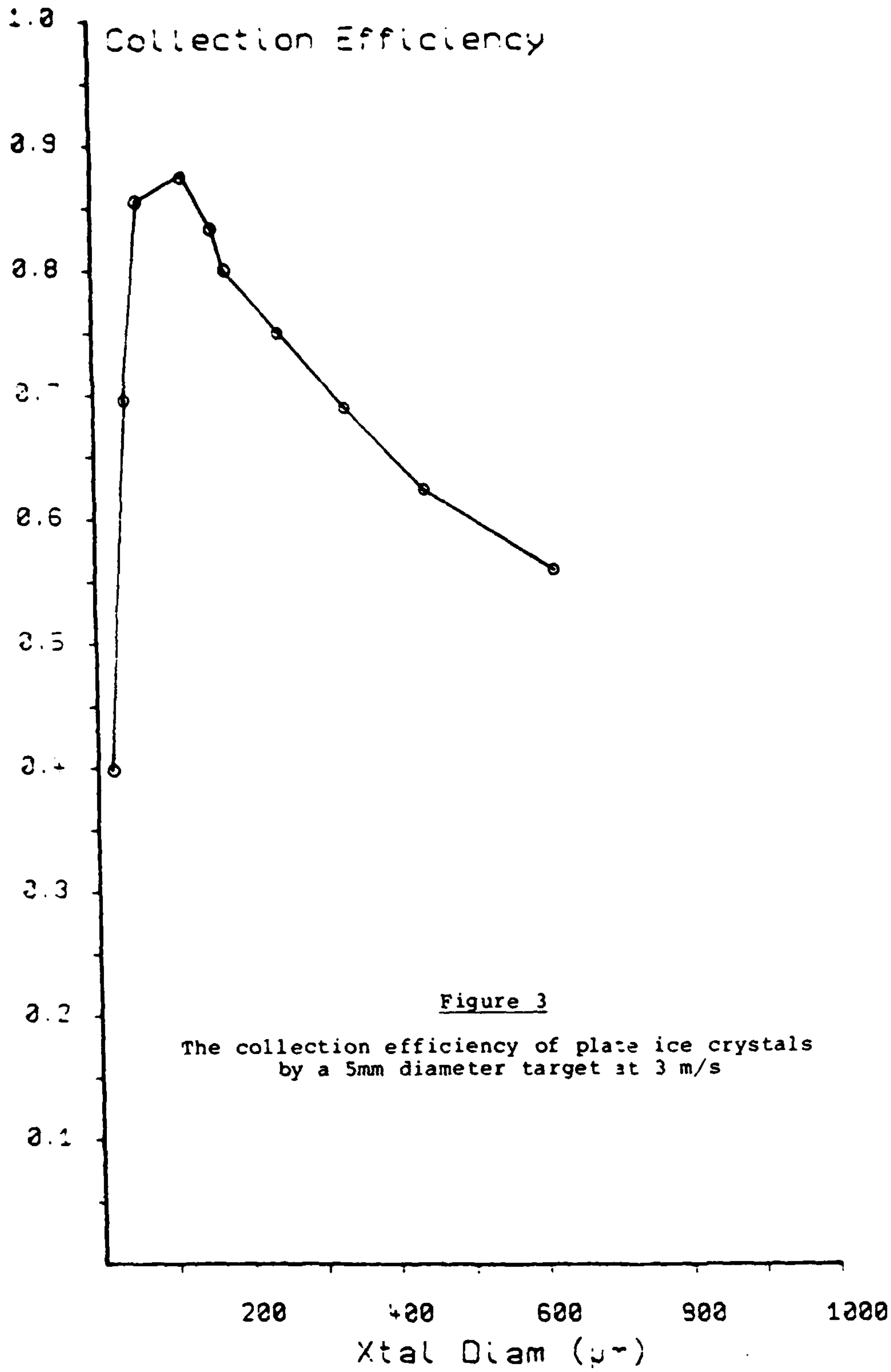


Figure 3

The collection efficiency of plate ice crystals by a 5mm diameter target at 3 m/s

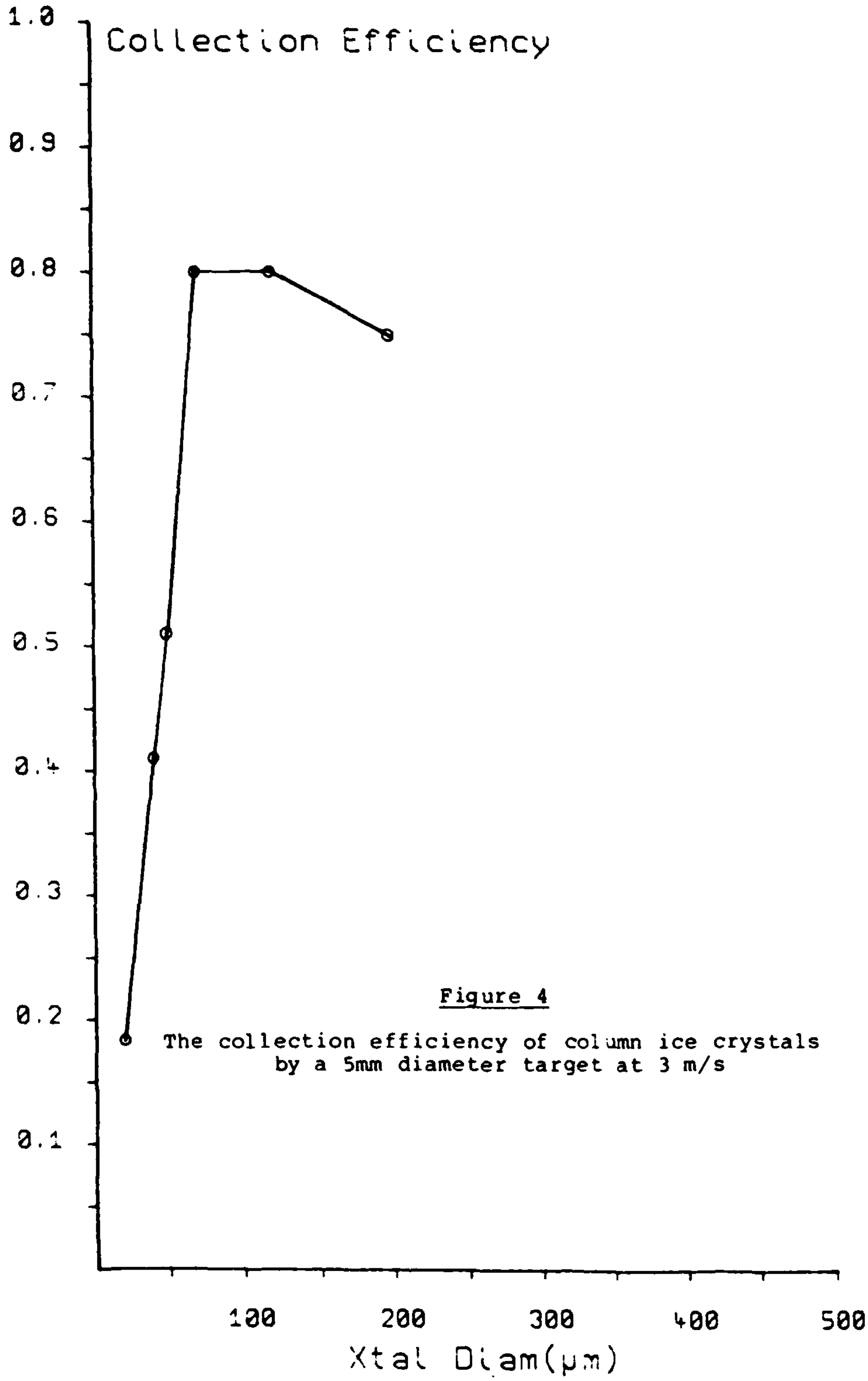


Figure 4

The collection efficiency of column ice crystals by a 5mm diameter target at 3 m/s

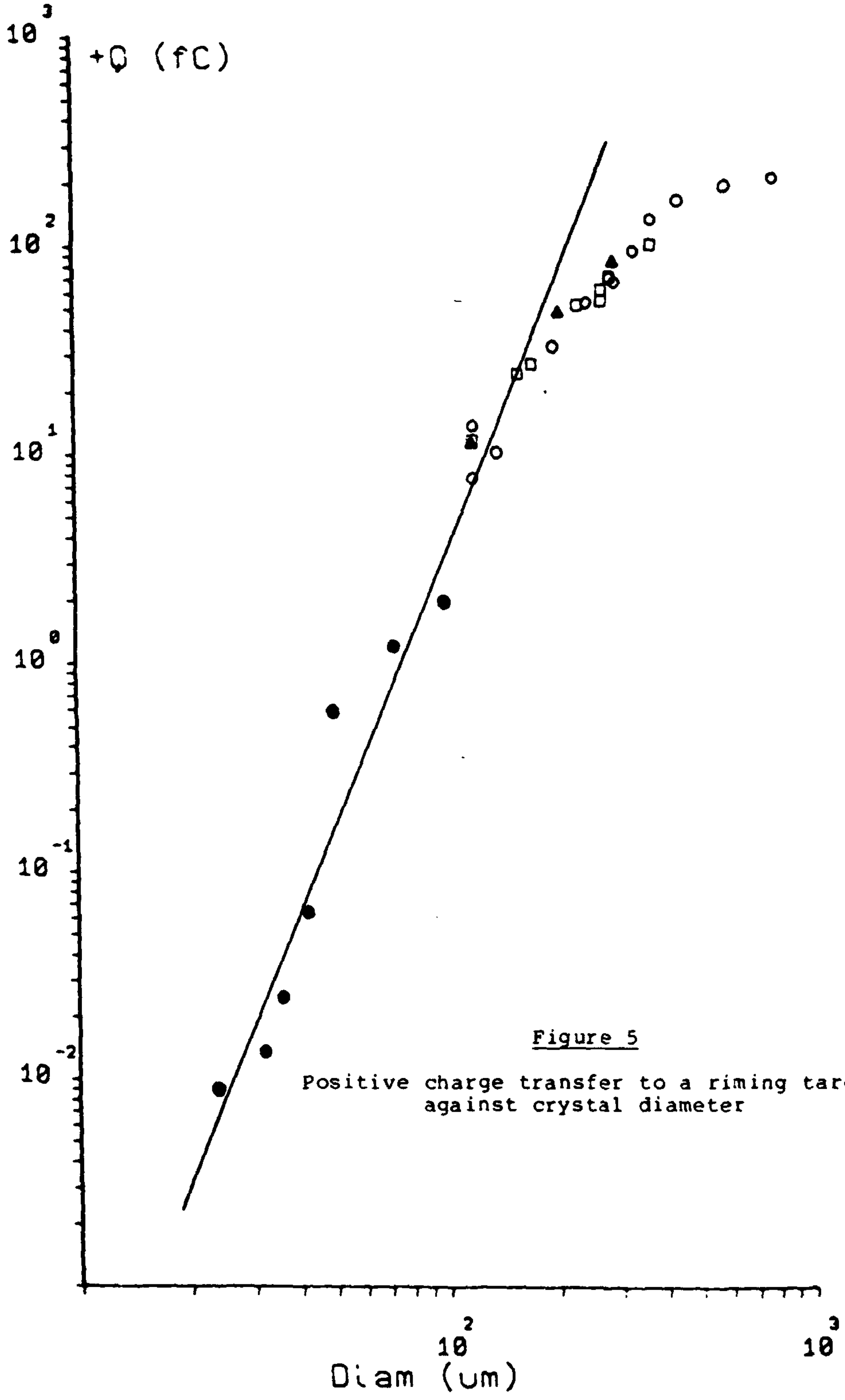
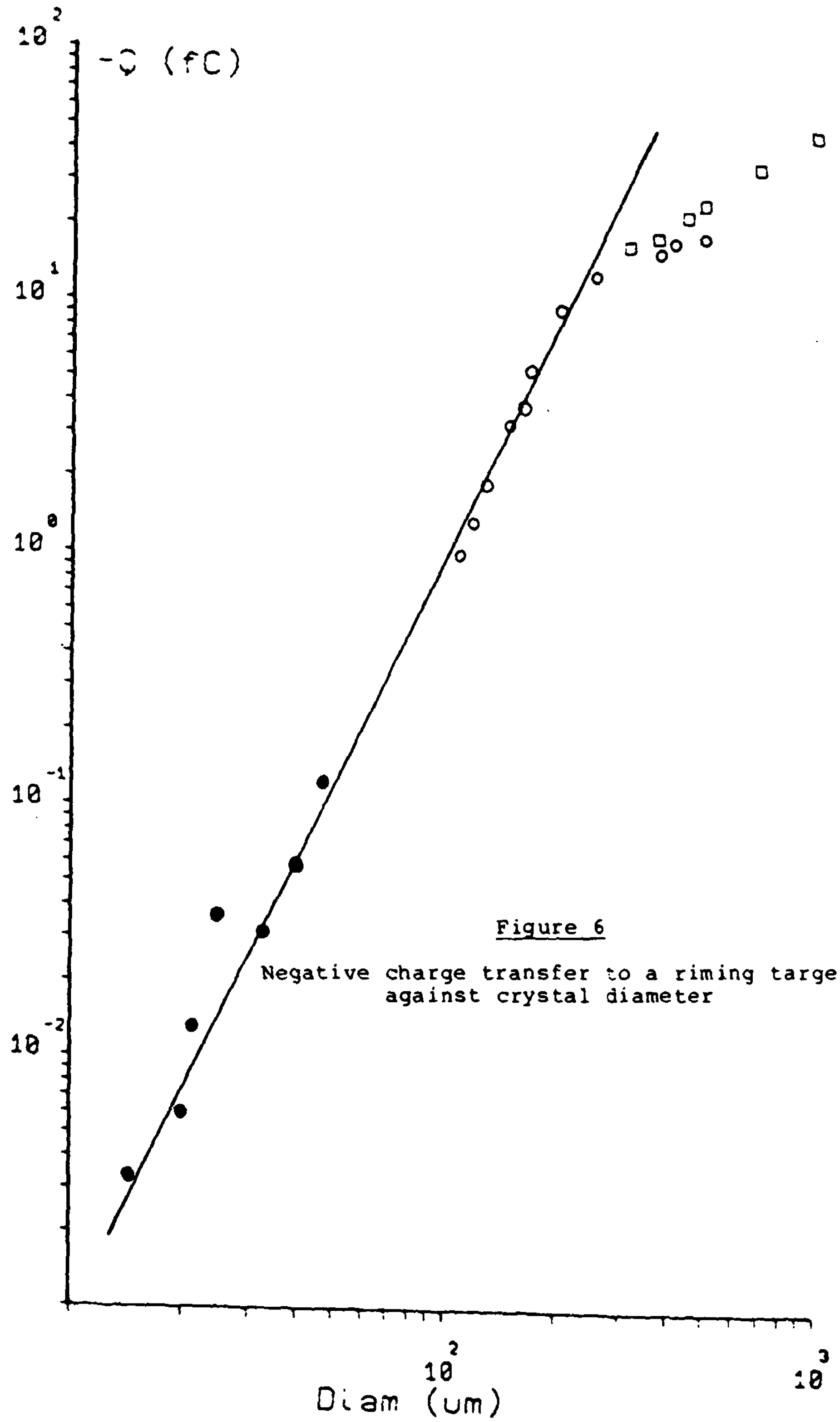


Figure 5

Positive charge transfer to a riming target against crystal diameter



<u>Figure 6</u>

Negative charge transfer to a riming target against crystal diameter

Figure 7

Photons detected per charge transferred against ice crystal size.

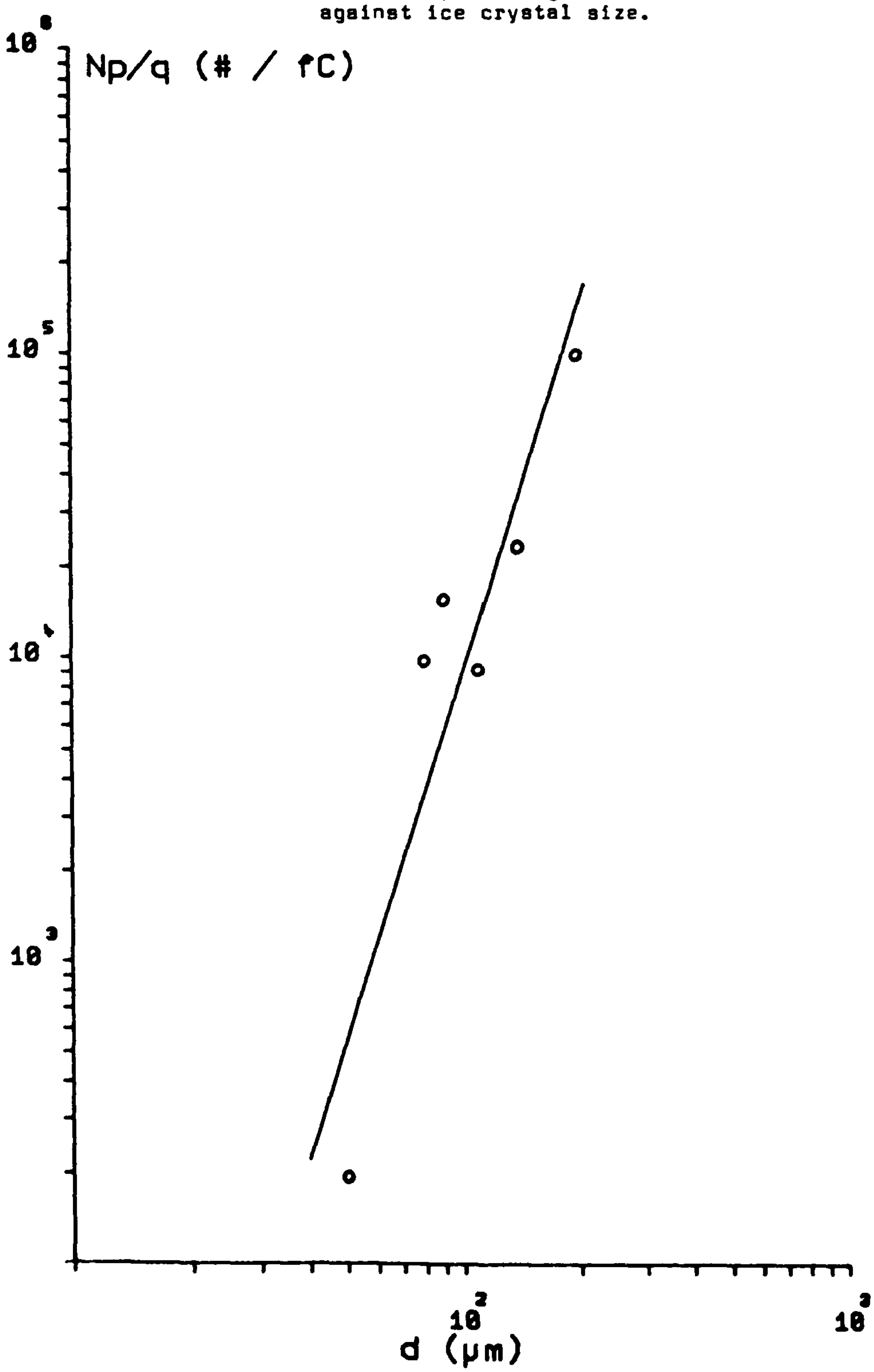


Figure 8

The distribution of charge transfer values when individual crystals bounce off an ice target